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## Buckling of WBK cored sandwich panels under longitudinal compression

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### Abstract

Buckling behaviors of WBK (Wire-woven Bulk Kagome) cored sandwiches under longitudinal compression are studied. Slender and short specimens are fabricated of mild steel wires and face sheets, and are fixed through copper brazing. And buckling experiments with axial compression are carried out. The failure mechanisms are analyzed by the theory and numerical simulation. Effects of eccentricity of loading or geometry, and fixings at both ends are investigated. Practical and physical meanings of the results and potential of WBK as a sandwich core are discussed.

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### 1. Introduction

Since Sypeck and Wadley in 2001 introduced a new kind of cellular metal ‘textile core’ (Sypeck and Wadley (2001)), a number of techniques have been developed to fabricate cellular metals using metallic wires. The new types of cellular metals were named ‘wire-woven metals’ by the authors. A few years later, the author’s group developed WBK, which stands for Wire-woven Bulk Kagome (Lee et al. (2007)). WBK is a wire-woven metal composed of helically formed wires arranged in parallel in six different directions evenly distributed in space, inherently having a 3D structure like a Kagome truss, whereas the textile core has a layered structure with 2D plain-woven wire meshes.

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The mechanical properties of WBK under compression or shear loading were investigated to show that its strength is much higher than those of conventional cellular metals and even comparable to those expected for use in the ideal Kagome truss structures composed of straight struts and frictionless joints (Lee et al. (2007), and Lee and Kang (2009)). Also, WBK was evaluated to determine its performance as a core material for sandwich panels and the optimal design methodology of WBK-cored sandwich panels was studied to obtain its maximum bending strength for a given weight or the least weight for a given bending load (Lee and Kang (2009)). However, the buckling behavior of WBK-cored sandwich panels against in-plane compression has never been investigated.

A honeycomb core has strength and stiffness under shear comparable to those under compression. Consequently, a honeycomb core in a sandwich is not likely to be sheared under buckling load. Also, the size of the cells is generally too small to allow dimpling to occur on the face sheets. Instead, the sandwich often buckles due to face wrinkling induced by the poor strength at the adhesive bond between the honeycomb core and the face sheets (Bitzer (1997)).

Recently, Cote et al. (2007) and Biagi and Bart-Smith (2012) investigated the buckling behaviors of metallic sandwich panels with 2D and 3D truss cores. The cores were metallurgically well bonded with the face sheets and debonding never occurred in their studies. However, their sandwich panels were vulnerable to elastic or plastic face wrinkling because the truss cores were single-layered, having joint intervals which were comparable to the core heights.

The shear strength and, especially, the stiffness of WBK are not as high as those of honeycomb cores or single-layered truss cores (Lee and Kang (2009), and Lee and Kang (2013)). Consequently, the WBK-cored sandwich panels subjected to buckling loads are expected to behave differently from the sandwich panels with other cores. Recently, we investigated the feasibility of application of WBK-cored sandwich panels in shipbuilding (Kang (2012)). As a part of the results, this article presents their buckling behaviors. Classical theories are introduced, and experimental and numerical results are presented. The effects of aspect ratio, strength and stiffness of the WBK core, the constraint of the core near the ends, and eccentricity on the resistance of the sandwich panels against buckling and post-buckling behavior are evaluated.

## 2. Theory

Figure 1(a) depicts macro elastic buckling. According to Euler's formula, the critical load,  $P_{cr}^E$ , is given as a function of the length,  $L$ , and the bending stiffness,  $D$ , as follows:

$$P_{cr}^E = k^2 \frac{\pi^2 D}{L^2}, \text{ where } D \approx E_f \frac{bt_f h^2}{2(1 - \nu_f^2)} \quad (1)$$

and  $k$  denotes the constraint at both ends of the sandwich panel,  $k=1$  or  $2$  for rotation free or fixed ends, respectively.  $E_f$  and  $\nu_f$  are the Young's modulus and Poisson's ratio of the face sheets, respectively.  $b$ ,  $h$  and  $t_f$  are the width, distance between the centroids of the upper and lower face sheets, and thickness of the face sheets. If the shear stiffness of the core,  $A_c G_c$ , is so low as to be comparable to  $P_{cr}^E$ , the sandwich panel will buckle with core shear deformation, as shown in Figure 1(b). Then, the critical load for macro elastic buckling is modified as follows (Wicks and Hutchinson (2001)):

$$P_{cr}^S = P_{cr}^E \frac{1}{1 + \frac{P_{cr}^E}{A_c G_c}} \quad (2)$$

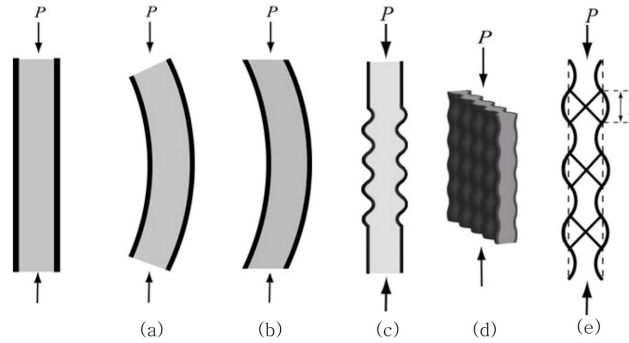


Figure 1: Modes of buckling of sandwich panels subjected to in-plane compression.

If the stress in the face sheets reaches the yield strength of the face material before macro elastic buckling occurs, the sandwich panel will fail by macro plastic buckling, and the critical load is given by:

$$P_{cr}^P = A_f \sigma_f^o = \frac{4t_f b \sigma^o}{\sqrt{3}} \quad (3)$$

where  $\sigma^o$  and  $\sigma_f^o$  are the yield strength of the mother material of the face sheets and that modified by the factor,  $\frac{2}{\sqrt{3}}$ , which is introduced under the assumption of plane strain condition (Cote et al. (2007)). Because the sandwich

panel has the thin face sheets and a high bending modulus due to the thick core, the panel may fail by local buckling of the face sheets such as face wrinkling or face dimpling, as shown in Figure 1(c) and 1(d). According to Allen (1969), the critical load corresponding to face wrinkling is given by:

$$P_{cr}^W = A_f \sigma_f^W = 2t_f b \times 0.58 (E_f E_c^2)^{\frac{1}{3}} \quad (4)$$

And, according to Wicks and Hutchinson (2001), the critical load corresponding to face dimpling is given by:

$$P_{cr}^D = A_f \sigma_f^D = 2t_f b \times 0.255 \frac{\pi^2 E_f}{1 - \nu_f^2} \left( \frac{t_f}{\text{cell size}} \right)^2 \quad (5)$$

Because the WBK core is bonded with the face sheets by copper brazing of sufficient strength, the core is never expected to debond from the face sheets during in-plane compression. Hence, the possibility of dimpling due to face-core debonding, which is often observed in honeycomb-cored composite sandwiches, is ruled out.

### 3. Experiments

The mother material used to fabricate both WBK cores and face sheets was low carbon mild steel. The fabrication process of the WBK cores was the same as in another article on the bending behavior of sandwich panels with discontinuous WBK-cores (Lee et al. (2013)). The brazed WBK cores were trimmed and ground to flatten the upper and lower surfaces. Finally, each WBK core was brazed again with a pair of face sheets of thickness  $t_f = 0.5\text{mm}$  and wedge-shaped plugs at the ends.

Two kinds of specimens were prepared, Type I and Type II. Type-I specimens were relatively short and thick. The length, width and thickness of their cores were  $L_c = 200\text{ mm}$ ,  $b = 82.4\text{mm}$  and  $H_c = 32.7\text{ mm}$ . Type-II specimens were relatively long and thin. The length, width and thickness of their cores were  $L_c = 450\text{ mm}$ ,  $b = 50\text{mm}$  and  $H_c =$

10.7 mm. Both types of specimens had plugs with sharp wedges at the ends. To investigate the effect of the constraint of the WBK core near the plugs, the cores near the plugs of some specimens were filled with epoxy.

Each specimen was installed between a pair of V-shaped blocks so that the wedge ends of the plugs tightly contacted the valleys of the blocks. Then a compressive load was applied by displacement control at 0.002 mm/second. The load-displacement behavior was monitored by a digital data logger.

## 4. Results

### 4.1. Type-I specimens

Figure 2 shows the load-displacement ( $P$ - $\delta$ ) curves measured during in-plane compression and the minimum level of critical loads estimated by the equations mentioned above for Type-I specimens. The two measured  $P$ - $\delta$  curves are substantially different except for the initial portions of the curves because of the epoxy filling in the WBK core near the edges. Figure 3 shows the deformed specimen with epoxy-filled near the plugs.

The  $P$ - $\delta$  curve of the unfilled specimen deviated from the curve of the filled specimen at the load near  $P = 2\text{ kN}$  because of early local buckling of the face sheets near the plug. Consequently, the peak load is substantially lower than that of the epoxy-filled specimen. In the specimens, some wires on the lateral sides of the WBK core were not bonded during the second brazing process. In fact, we tried brazing the WBK core several times using other specimens, but failed to bond all the wires on the plugs, which seemed to be attributed to difference of thermal capacity between the thin wires and the thick plugs. As shown above, epoxy filling effectively prevented the early local buckling of the face sheet near the plug; this means that the imperfect bonding on the lateral sides of the WBK core caused the early local buckling and the subsequent lower peak load.

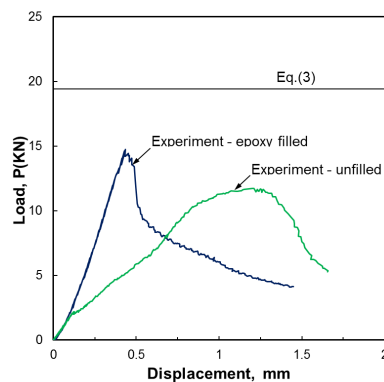


Figure 2: Load-displacement curves measured during in-plane compression of Type-I specimens.

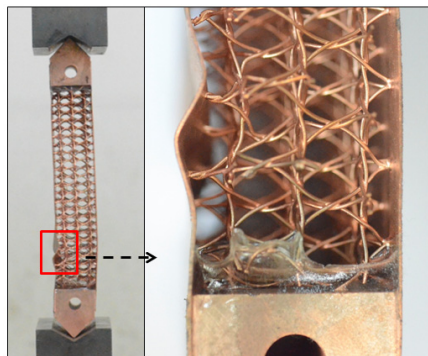


Figure 3: A deformed Type-I specimen with epoxy-filled near the plugs.

The analytic solutions of Eqs. (1) to (5) can be applied to estimate critical loads. Eq. (1) gave an excessively high critical load for macro elastic buckling,  $P_{cr}^E = 860.8$  kN. Eq. (2), modified for the core shear effect, gave the critical load,  $P_{cr}^S = 188.8$  kN, which is significantly lower than  $P_{cr}^E$ , but still very high. Eq. (4) gave the critical loads for face wrinkling,  $P_{cr}^W = 139.3$  kN. Eq. (5) gave the critical load for face dimpling,  $P_{cr}^D = 20.9$  kN, which is slightly higher than the minimum critical load. Eq. (3) gave the minimum critical load,  $P_{cr}^P = 19.4$  kN for macro plastic buckling. The minimum critical load is presented in Figure 2, which is about 30% higher than that measured from the epoxy-filled specimen. Considering experimental scattering and the simplicity of the equation, the error is acceptable.

#### 4.2. Type-II specimens

Figure 4 shows the load-displacement ( $P$ - $\delta$ ) curves measured from Type-II specimens during in-plane compression, and the level of critical load for the macro plastic buckling, which is the minimum of the critical loads estimated for various failure modes as was in Type-I specimens. The measured  $P$ - $\delta$  curves are similar to each other, regardless of the epoxy-filling in the WBK core near the edges. It is interesting that the epoxy unfilled specimen had a higher peak load than the filled specimen, although the  $P$ - $\delta$  curve of the unfilled specimen deviated slightly from the curve of the filled specimen at a very low load level because of the early local buckling of the face sheets near the plug, similar to that observed in the Type-I specimens. In fact, the local buckling of the face sheets stopped after a while and never proceeded to cause the final failure, but the unfilled Type-II sandwich panel remained almost intact until the load level reached the peak,  $P_{max} = 5.7$  kN. After the peak loads, core shear initiated at a region near the upper or lower end in both specimens, and expanded as the applied displacement increased.

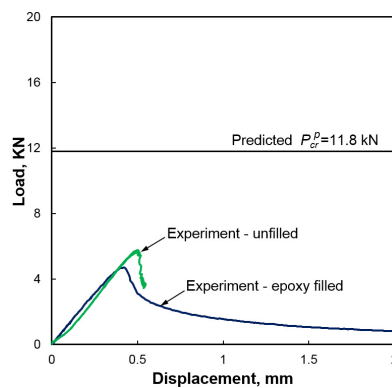


Figure 4: Load-displacement curves during in-plane compression of Type-II specimens.



Figure 5: Deformed Type-II specimens with epoxy-filled near the plugs.

Figure 5 shows the deformed Type-II specimens with core shear after the tests and an enlarged view of the epoxy-filled end near the plug. The epoxy filling delayed the initiation of core shear near the plugs. Core shear was the mechanism of Type-II specimens that accommodated the applied displacement, although core shear was never the main failure mechanism governing the peak loads. Core shear seems to stem from low shear rigidity and shear strength of the WBK core, which will be discussed below. Eq. (1) gave the critical load for macro elastic buckling,  $P_{cr}^E = 20.2$  kN, which was much lower than that for the same buckling mode of Type-I specimens. Eq. (2), modified for the core shear effect, gave the critical load,  $P_{cr}^S = 14.8$  kN, which is somewhat higher than the minimum level of the critical loads,  $P_{cr}^P = 11.8$  kN, for macro plastic buckling. The minimum critical load is presented in Figure 4. Eq. (4) gave the critical loads for face wrinkling,  $P_{cr}^W = 84.5.3$  kN. Eq. (5) gave the critical load for face dimpling,  $P_{cr}^D = 12.7$  kN, which is slightly higher than the minimum critical load as was for Type-I specimens. As shown in Figure 4, however, the critical load given by Eq. (3) for macro plastic buckling greatly deviated from the measured ones. In fact, the deformed configuration estimated by FEA performed in the authors' preliminary study was never the same as those observed from the experiments, shown in Figure 5. The difference was due to the small initial deflection in the specimens, which will be elaborated in near future.

## 5. Conclusion

- For both types, the peak loads were governed by macro plastic buckling. However, the critical loads of Type-II specimens estimated by the simple equation showed substantial errors.
- Epoxy filling effectively prevented early local buckling of the face sheets near the plug of Type-I specimens, implying that the imperfect bonding on the lateral sides of the WBK cores caused the early local buckling and the subsequent lower peak loads.

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## References

- Allen, H.G. Analysis and Design of Structural Sandwich Panels 1st Ed, London: Pergamon Press, 1969.
- Biagi, R., Bart-Smith, H. 2012. "In-plane column response of metallic corrugated core sandwich panels," *Int. J. Solids Struc.* 49: 3901–3914.
- Bitzer, T. Honeycomb Technology, London: Chapman & Hall; 1997.
- Cote, F., Biagi, R., Bart-Smith, H., Deshpande, V.S. 2007. "Structural response of pyramidal core sandwich columns," *Int. J. Solids Struc.* 44: 3533–3556.
- Kang, K.J. Evaluation of material properties for application of WBK and fabrication of proto type structures. Final report to Samsung Heavy Industry; Chonnam National University South Korea: 2012.
- Lee, B.K., Kang, K.J. 2009. "A parametric study on compressive characteristics of wire-woven bulk Kagome truss cores," *Composite Structures*, 92: 445–453.
- Lee, M.G., Kang, K.J. 2013. "Feasibility of a wire-woven metal for application as a sandwich core," Submitted to *Int. J. Mech. Sci.*
- Lee, M.G., Yoon, J.W., Han, S.M., Suh, Y.S., Kang, K.J. "Bending Effects of Gaps between Discontinuous WBK Cores upon Bending Behavior of Sandwich Panels," *MetFOAM 2013* held in Raleigh, NC, June 23–27. 2013.
- Lee, Y.H., Kang, K.J. 2009. "A wire-woven cellular metal: part-I, optimal design for applications as sandwich core," *Materials & Design*, 30: 4434–4443.
- Lee, Y.H., Lee, B.K., Jeon, I., Kang, K.J. 2007. "Wire-woven bulk Kagome (WBK) truss cores", *Acta Materialia*, 55: 6084–6094.
- Sypeck, D.J., Wadley, H.N.G. 2001. Multifunctional microtruss laminates: Textile synthesis and properties. *J. Mater. Res.* 16: 890–897.
- Wicks, N., Hutchinson, J.W. 2001. "Optimal truss plates," *Int. J. Solids Struc.* 38: 5165–5183.